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The Role of Attention in the Development of Short-Term Memory: Age Differences in the Verbal Span of Apprehension

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In previous studies of memory span, participants have attended to the stimuli while they were presented, and therefore have had the opportunity to use a variety of mnemonic strategies. In the main portion of the present study, participants (first- and fourth-grade children, and adults; 24 per age group) carried out a visual task while hearing lists of spoken digits and received a post-list digit recall cue only occasionally, for some lists. Under these conditions, list information presumably must be extracted from a passively held store such as auditory sensory memory. The results suggest that each individual has a core memory capacity limit that can be observed clearly in circumstances in which it cannot be supplemented by mnemonic strategies, and that the capacity limit appears to increase with age during childhood. Other, attention-demanding processes also contribute to memory for attended lists.

INTRODUCTION

Years of effort have been devoted to an understanding of short-term memory (see Case, 1995; Cowan, 1995; Engle and Oransky, 1999), by which we mean the temporarily increased availability of information in memory that may be used to carry out various types of mental tasks. By all accounts, the capacity of short-term memory is limited, which constrains the quality of human performance. Researchers do not agree, however, on any particular theoretical explanation of the observed limitations in short-term memory. Proposals have included storage capacity limitations (Case, 1995; Halford, Maybery, & Bain, 1988; Miller, 1956), time limitations because of memory decay (Baddeley, 1986), limitations in the speed and efficiency of mnemonic strategies such as rehearsal (Baddeley, 1986) or short-term memory search (Cowan et al., 1998), limitations in knowledge about the stimuli (Hulme et al., 1997), and limitations in how well attention can be controlled and irrelevant information inhibited (Engle, Conway, Tuholski, & Shisler, 1995). There also are principles of item distinctiveness, retroactive and proactive interference between items, and mental structure, which are certain to influence performance on memory tasks in general, including those taken to index short-term memory processes (Baddeley & Hitch, 1993; Cowan, Wood, Nugent, & Treisman, 1997; Nairne, Neath, Serra, & Byun, 1997). It is difficult to determine which limitations are critical in particular tasks.

The debate about the nature of short-term memory limitations has important implications also for the development of short-term memory in childhood. It has long been known that performance on simple short-term memory tasks, such as the digit span task that is included in tests of intelligence, increases with age in childhood (Dempster, 1985). The explanations of short-term memory development, however, have varied widely (Cowan, 1997). They have focused primarily on increases in knowledge, metaknowledge, and strategies (e.g., Case, Kurland, & Goldberg, 1982; Naus, Ornstein, & Aivano, 1977), with considerable emphasis also on the speed of various processes (e.g., Cowan et al., 1998; Gathercole & Baddeley, 1993; Hitch & Towse, 1995; Kail & Park, 1994). What has been relatively rare, though, is research emphasizing the possibility of developmental change in the capacity of short-term memory; that is, the number of items that can be held in mind at a time (Cowan, 1999; Halford et al., 1988; Halford, Mayberry, O'Hare, & Grant, 1994; Pascual-Leone, 1970).

It is difficult to identify one basic short-term memory faculty separated from all others. Nevertheless, considerable research suggests that there is an identifiable faculty: a short-term memory store with a capacity considerably smaller than the typical digit span, as discussed by Broadbent (1975). As Miller (1956) noted, adults can remember lists composed of about seven meaningful items or "chunks." That memory limit is undoubtedly reached, however, with the use of a variety of mnemonic strategies. Participants may enhance memory by repeating items to themselves and forming new, meaningful associations between items shortly after they are presented (i.e., through rote and elaborative rehearsal; see Naveh-Benjamin & Jonides, 1984). When one examines aspects of short-term memory that are unlikely to be influenced by such strategies, one finds a limit in adults

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of about three or four items, not seven. Evidence of this limit includes the maximum number of items that participants group together in recall, the maximum list length resulting in errorless performance, and the list length for which proactive interference from previous, similar items is not obtained (Broadbent, 1975; Halford et al., 1988). This memory limit might reflect the amount that can be subsumed in the focus of attention at one time (Cowan, 1995). It also appears to be the same as what Sperling (1960) called the "span of apprehension." In the present article, developmental changes in this span of apprehension will be examined in children and adults.

Sperling's (1960) well-known study was designed to examine visual sensory memory, and it demonstrated that that form of memory has a very large capacity. The study, however, also established a span of apprehension. The procedure involved very-briefly-presented character arrays. In a "partial report" procedure, a postarray cue indicated which row of the array to report. With a short postarray delay before the cue, participants could typically report at least three of the items in a single cued row, suggesting that most items in the array were temporarily available for report. In the "whole report" procedure, there was no post-array cue, and the entire array was to be reported. However, participants could only report about four items in the entire array. In the partial report condition, increases in the delay before the cue impaired performance and, when the cue was delayed 1 s, the proportion of the cued row that was recalled was no greater than recall of the same row in the whole report condition. This suggested that the whole report limit represented a basic capacity limit of about four items.

Sperling inferred that the mechanism is as follows. A large number of items is at first represented in an unprocessed form in sensory memory storage. This memory, however, quickly fades. A limited number of items (about four in adults) can be processed from this sensory store, and they become represented in a capacity-limited short-term store. Items must be entered into capacity-limited storage before they fade from sensory memory, and a postarray cue in the partial report procedure simply limits the items that the participant is asked to process before sensory memory fades. The same processes appear to take place in audition. Darwin, Turvey, and Crowder's (1972) results using spatiotemporal arrays of spoken items were analogous to those of Sperling (1960), though the value of the partial report cue persisted in this modality until the cue was delayed by 4 s (as compared to 1 s in vision). This suggests that it is storage capacity, rather than the rate of information transfer to a categorized short-term store, that is critical for the observed whole report limit.

There is a logical explanation for why the span of apprehension that Sperling (1960) and Darwin et al. (1972) observed was appreciably smaller than the short-term memory limit that Miller (1956) observed. Miller concentrated on procedures in which items were presented one at a time. Under those circumstances, mnemonic strategies, like rehearsal, can be used during the list presentation. In contrast, when an array is presented, there are too many concurrent items for mnemonic strategies to be applied efficiently. The number recalled then may represent the number that can be processed in parallel in a very short time, with little chance of enhancing performance with strategies requiring serial processing.

The presentation of spatial or spatiotemporal arrays may cause particular difficulties when the participants are young children, who may become confused about how to report the items. To examine the development of the span of apprehension in a simpler manner, we have developed a modification of the whole report procedure that permits the serial presentation of items. Lists of spoken digits were presented. To limit the contribution of mnemonic strategies, in one condition the participants were asked to ignore most of the spoken lists and play a silent computer game, both to hold attention and to tie up articulatory processes that otherwise could be used for covert verbal rehearsal. Only occasionally within this procedure, the game was interrupted by a postlist signal to recall the most recent list of digits. We presumed that participants could do this by searching through a sensory memory record of the series of recent spoken events to identify some of the digits, which could then be saved in a capacity-limited form of storage. The results suggest that such a process was indeed possible, and that a procedure logically analogous to Sperling's whole report procedure works for serial lists of spoken stimuli.

Past research gives few clues about the ages at which capacity limits in storage should increase. Memory span increases steadily during the ages of 3 to 10 years (e.g., Dempster, 1985), but the basis of this increase is unclear. We investigate whether a developmental change in the short-term memory capacity limit is a viable account of at least some of the developmental change in span.

Performance also was examined in a condition in which the spoken items were to be attended when they were presented. The magnitude of capacity-limited storage should be the same for both attended and unattended speech; in both cases, sensory memory for the entire list is attended at the time of recall. Additional encoding in the attended-speech condition, however, should allow the formation of more abstract, phonologically- and semantically-based memory representations during the presentation period that also can be drawn upon at the time of recall, enhancing recall in that condition. The present research should indicate the role of attention during encoding in short-term verbal recall.

The present procedure was a modification of one used previously to examine the development of auditory sensory memory (Saults & Cowan, 1996). That procedure differed from the present one primarily in that the spoken stimuli occurred individually rather than in groups. In that study, the ability to recollect the last spoken item decreased across post-item delays more rapidly in younger children than in older children or adults. Our present sample of participants included the youngest children who could carry out the procedure reliably (first graders) and adults. A fourth-grade group also was used because these children should be intermediate in maturity and performance (see Saults & Cowan, 1996). It seems clear that changes in brain development that could underlie a growth in capacity continue during the age range studied here (Rabinowicz, 1980; Thatcher, 1992; Yakovlev & Lecours, 1967).

METHOD

Participants

The participants were 24 first graders (10 male, 14 female, *mean* age = 88.88 months, *SD* = 3.73), 24 fourth graders (8 male, 16 female; *mean* age = 122.92 months, *SD* = 5.22), and 24 young adults (12 male, 12 female; *mean* age = 247.33 months, *SD* = 31.34). The children received $10 and a book for their participation, whereas the adults completed the study for course credit in their introductory psychology classes. Results from seven other children were excluded: two from first graders who did not follow instructions, one from a first grader who became bored and quit before the experiment was complete, and four (one first grader and three fourth graders) because of computer malfunctioning.

Apparatus and Stimuli

Except for a noncomputerized span pretest, the experiment used a Macintosh II computer to digitize spoken digits and present them to the participant in a sound-attenuated booth over TDH-39 audiological headphones at 55 dB(A) as measured with a sound level meter and earphone coupler. Each digit was spoken in the same male voice and was supplemented by silence so that the digit's presentation window was exactly 500 ms. The digits were presented in lists with lengths defined relative to the participant's span as measured in the pretest: span − 3 (i.e., "span minus three"), span − 2, span − 1, and span. For example, for a participant with a span of five items, the shortest, "span − 3" lists were two items long, and lists of three, four, and five items also were presented. Within each list the digit onset-to-onset intervals were 500 ms.

The basic experimental setup will be described briefly here, and then the somewhat lengthy sequence of experimental phases will be explained in more detail in the Procedure section. The three main tasks to be described in the present section are the attended speech task, the unattended speech task, and the primary visual task.

Attended-speech task. In the attended-speech task, each trial began with a 1-s clear screen and a 2-s *get ready* sign. A spoken list was then presented and, 2 s after the onset of the last list item, a memory response display appeared. This display consisted of a row of small boxes (each 12 mm wide and 15 mm tall, separated by small spaces), with one box representing each item in the just-presented list. The participant was to type the correct digits using the computer keyboard's numerical keypad. When each digit was typed, it appeared in the next vacant response box on the screen. It was possible to change an answer using the tab key to cycle through the serial positions, before reporting the entire list response by pressing the enter key. The response in each serial position was scored as correct only if the digit presented in that serial position was typed into the correct box on the screen. Pressing the enter key also initiated the next trial.

Unattended-speech task. In the unattended-speech condition, multiple lists were presented in succession, and the memory response display appeared only occasionally, not after every list. Each sequence culminated in a memory test for only the last list in the sequence. Silent periods of 1, 4, and 7 s were interspersed between lists, with each of these three interlist intervals occurring an equal number of times in a pseudo-random order. Each sequence of lists lasted 45 to 100 s and ended in a memory test display on the computer screen, exactly as in the attended-speech condition. (The duration of the sequence of lists was intentionally varied in this way so that the participant would not be able to predict which list would be tested.) The computer imposed a delay of about 1 min while the next trial's stimuli were loaded, and then the participant initiated the next trial when ready by pressing the shift key. Lists of each of the four predetermined lengths occurred an equal number of times in each sequence.

Primary visual task. This task was basically as described by Saults and Cowan (1996, Experiment 2). Sets of four pictures appeared in the top left, top right, bottom left, and bottom right quadrants of the screen. The conventional names of these four pictures did not rhyme with one another. A picture that appeared in the center of the screen had a name that rhymed with one of the four surrounding pictures. The task was to use the computer mouse to select the surrounding picture with the rhyming name, and both the accuracy and reaction times (RTs) were recorded. Whether the participant was correct or not, the display went on to the next trial as soon as a response was entered. For a series of visual trials accompanying the auditory sequence leading up to and culminating in an auditory memory trial, only the central picture changed; whereas between series, the surrounding set of pictures changed. The pictures illustrated objects that were very familiar to children, and children were made familiar with the names before the task was used experimentally. Each correct response was signaled by a star that appeared at the right-hand side of the screen; for an incorrect response, no star appeared. For the children, but not the adults, a further entertaining event ensued when the task ceased. A round, animated face in side view (i.e., a "pac-man" figure) ate the stars and burped up one bubble for every 10 stars and another bubble for any remainder, with each bubble representing a sticker that the child would receive at the end of the series of visual trials.

In the main, unattended-speech phase of the experiment, the visual task was carried out during the presentation of spoken digits. The participants were asked to try to ignore the digits until a recall cue was presented, in order to concentrate on the visual task. The surrounding pictures remained the same for all visual task trials leading up to one auditory memory test trial. Occasionally within the spoken series, as described above, the visual task was abruptly replaced with the memory response display (2 s after the onset of the last spoken item), so that the participant could not predict what spoken list would be tested until shortly after that list had ended.

Procedure

There were nine phases to the experiment: (1) a digit span pretest, (2) Part I of auditory task familiarization and practice, (3) an initial set of attended-speech control trials, (4) Part II of auditory task familiarization and practice, (5) visual task familiarization and practice, (6) an initial set of visual-task-alone control trials, (7) the main experimental phase, in which participants carried out the visual task in the presence of unattended speech and only occasionally were tested on the spoken digits, (8) a second, final set of visual-task-alone control trials, and (9) a second, final set of attended-speech control trials. These phases will be described in turn.

Span pretest. The span pretest was administered live, with digits spoken in the same predetermined, pseudo-random order for each participant at the rate of 1 item per second, in a monotone except for a downward inflection on the last item to serve as a recall cue. The participant's response in this pretest phase was spoken aloud. Beginning with three digits, the participant received three lists of a particular length. If any one of the three was repeated correctly, the next list length was administered, and the span was taken as the longest list repeated correctly, up to a maximum of nine. This integer span was used to set the list lengths in the main part of the experiment.

Auditory task familiarization and practice, Part I. In this step, the participant became familiar with the digitized spoken digits and the keypad. Each time a digit was heard, the participant was to press the corresponding key. Each of the nine digits was heard twice in this phase, and the participant was to try to find the keypad locations.

Initial attended-speech control sequences. In this phase of the experiment, the participant heard 12 lists of digits, including three at each list length (span − 3, span − 2, span − 1, and span). The memory response display was as explained above.

Auditory task familiarization and practice, Part II. This step was an introduction to the fact that, in the unattended-speech condition, the participant would not be asked to respond to every list. Four lists were presented for each practice trial, with variable timing between lists as in the unattended-speech presentation conditions as explained above, and only the fourth list in each series was to be recalled. The instructions were as follows: "This part will be a lot like the last part. Just listen, and you'll hear a few groups of numbers instead of just one group of numbers. Listen and wait for the boxes, then type in the last group of numbers only, that is, the group that came right before the boxes. You won't know which is the last group until you see the boxes. There will be as many boxes as there are digits in the last group." This task included four trials, one at each list length, and then another set of four trials if the first four were not answered correctly.

Visual task familiarization and practice. The purpose of this phase was to teach standard names for the pictures that would be used in the primary task carried out in the unattended-speech condition, and to give practice in this primary task itself. First, the participant was to press the enter key, which resulted in the presentation of five pictures and, along with each one, its spoken name. The five pictures' names rhymed with one another. Then the participant was to say the names of the pictures aloud and try to memorize them. Fourteen sets of five pictures were presented in this way. If a participant stumbled or used the wrong word for a picture, the correct response was offered and the set of five was repeated again until it was done correctly. Next, participants carried out the visual task alone, as described above. The criterion for passing this phase was six trials correct, not necessarily in immediate succession.

Initial visual-task-alone control sequence. The visual task was presented for a period of just under 1 min. Participants were to make matches as quickly as possible "without missing too many." They were to guess if stuck rather than sitting for "too long."

Unattended-speech sequences. There were 16 auditory memory trials in this phase of the experiment. During each memory trial, the participant carried out the visual task and was to "try to ignore" the digit lists for a period of 45 to 100 s, which culminated in a memory response display that replaced the primary visual task. Then the participant was to use the numerical keypad to recall the last list that had been presented. The response display contained one box for every digit to be recalled.

The number of unattended digit lists that preceded the one that was probed remained the same for all participants; for the sixteen blocks there were 12, 14, 16, 10, 10, 16, 14, 14, 12, 16, 16, 12, 10, 10, 12, and 14 unattended lists that were not probed, respectively. The lengths of all of the lists presented depended, however, on the participant's span and were of lengths span − 3 (i.e., 3 less than span), span − 2, span − 1, and span, intermixed.

Final visual-task-alone control sequence. This was identical to the initial visual-task-alone sequence and again lasted about 1 min.

Final attended-speech control sequences. These were just like the initial attended-speech control sequences and again included 12 list-memory trials.

RESULTS

Memory Span Pretest

Because an integer value of span was needed to determine list lengths in the subsequent tasks, span in the pretest was taken as the longest list length repeated correctly by the participant. The distributions of memory spans and the mean spans are shown in Table 1. As is clear from the table, there was a developmental improvement in memory spans, $F(2, 69) = 22.67$, $MSE = 1.06$, $p < .001$. (All pairs of means were significantly different by Newman-Keuls tests, $p < .003$ in each case). The selected age groups display nearly equal steps in span increases, which could be expected to produce a high sensitivity to age differences in other measures.

Table 1 Distribution of Memory Spans in Each Age Group

	Span Group[a]						
Age Group	4	5	6	7	8	9	*Mean*
First grade	3	12	7	1	1	0	5.38
Fourth grade	2	4	6	7	4	1	6.42
Adult	0	0	2	13	7	2	7.38

[a] The number of participants in each age group with each span from 4 to 9.

Number Correct in Attended- and Unattended-Speech Conditions

In one method of analysis of the computer-administered memory tasks, each participant's number correct in each attention condition was calculated separately for each relative list length (span − 3, span − 2, span − 1, and span). This was done by (1) calculating the proportion correct at each serial position across all lists of a particular relative list length, and (2) adding the mean proportions across all serial positions. For a participant to be given credit for a particular item, it was not necessary that the entire trial be correct; only that the item be reported in the correct serial position. To illustrate how this number correct measure was calculated, consider the span − 1 list length for someone with a span of 5. The relevant lists would include four items. If the individual's proportions of items correct across all span − 1 trials were .5, .25, .75, and 1.0 items for serial positions 1 through 4, respectively, then for this list length the participant would be credited with a number correct equal to the sum of these proportions, or 2.5 items.

Figure 1 shows the means for each age, attention condition, and list length relative to span. The data contributing to the attended-speech means include the experimental phases both before and after the unattended-speech phase. Thus, each participant's results included 24 attended- and 16 unattended-speech trials, the latter having been very time-consuming to conduct. Children with the shortest span, four items (three first graders and two fourth graders) were omitted from the memory results because their shortest lists were only one item long. The means changed little, however, when those children were included.

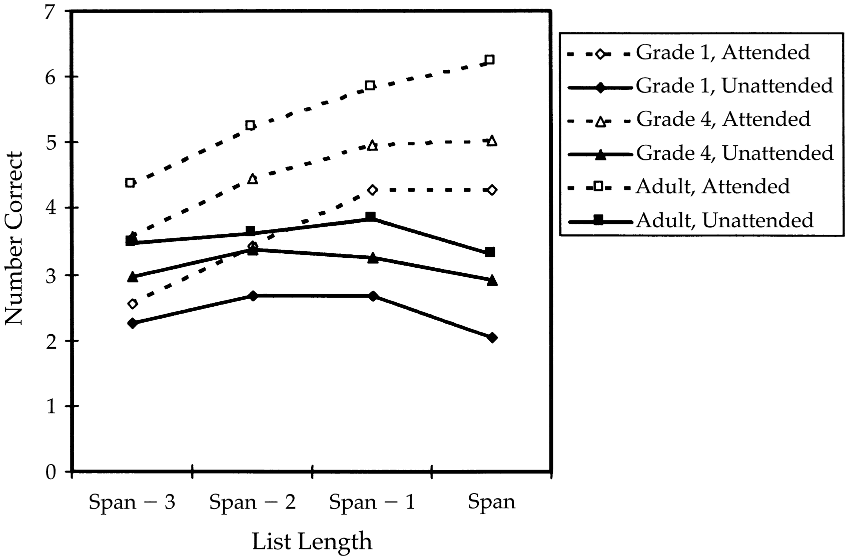

Figure 1 Mean number of items recalled on trials at each relative list length for participants of three age groups (graph parameter) when tested on attended lists (dashed lines) and unattended lists (solid lines).

Correlations and reliability. Before analyzing the pattern of responses, it seems important to establish the reliability of the method. The correlation between a participant's longest pretest memory span and number correct in the attended-speech condition, averaged across list lengths, was $r(70) = .94$, suggesting a high reliability. The correlation between span and the mean number correct in the unattended-speech condition was lower at $r(70) = .52$, suggesting that not all of the same processes involved in span contributed to memory for unattended speech. Both correlations were significant.

The mean numbers correct for the attended, span-length lists in the computerized test (shown in Figure 1) cannot be compared directly to the pretested spans, given that the latter were recorded as the highest list length repeated correctly (because an integer value at a challenging level was needed). It seemed important to make this comparison to determine if the younger participants had any special difficulties with the keypad response mode, which was used in the latter test (whereas a spoken response was used for the span pretest). To this end, we examined the mean proportion of trials of each list length recalled correctly using the two measures (excluding one adult whose span protocol was lost). Results for first graders, fourth graders, and adults in the two tests were quite similar, both for lists of length span (span pretest, .52, .61, and .55 of the trials correct, respectively; computerized test, .54, .50, and .60, respectively) and for lists one below span (span pretest, .82, .78, and .78, respectively; computerized test, .86, .75, and .78, respectively). Shorter lists are uninformative because of ceiling effects at all ages. In analyses of variance (ANOVAs) comparing tests, younger participants were not found to be impaired with the computer keypad, relative to spoken responses.

Relative list length analyses. Several aspects of the data seem clear from Figure 1. First, performance in the unattended-speech condition remained relatively fixed across list lengths. The pattern in this condition is analogous to what Sperling (1960) observed with briefly presented spatial arrays of printed characters (i.e., a whole report limit that remained fixed across array sizes). The relatively fixed number correct regardless of list length can be viewed as a span of apprehension. The span of apprehension observed in our adults, about 3.5, is only slightly lower than that observed by Sperling, about 4.

Second, performance increased across list lengths in the attended-speech condition. That increase above the span of apprehension can be explained on the basis of attention-demanding mnemonic strategies and encoding that can be used to improve memory for speech. It seems reasonable to assume that the span of apprehension observed in the unattended-speech condition serves as a baseline estimate of capacity, contributing a certain amount to performance regardless of the direction of attention during encoding, and that attentive encoding raised performance above that baseline for attended speech.

Third, although the pattern of performance was similar across ages, the level of performance improved with age. In the unattended-speech condition, this suggests an age difference in effective capacity (i.e., span of apprehension).

One can further ask whether the developmental processes contributing to memory development were the same in both attention conditions. If an increase in the span of apprehension is sufficient to account for memory development, then the magnitude of the age effect should be the same in the attended- and unattended-speech conditions. As an initial means to investigate this question, an ANOVA on the data illustrated in Figure 1 was carried out with age as a between-participant factor and with attention condition (attended- versus unattended-speech) and relative list length (span − 3, span − 2, span − 1, and span) as within-participant factors. The basic pattern, shown in Figure 1 and Table 2, was confirmed. There was an effect not only of relative list length, $F(3, 192) = 47.07$, $MSE = 0.48$, $p < .001$, but also an attention condition × relative list length interaction, $F(3, 192) = 80.39$, $MSE = 0.26$, $p < .001$, produced by the divergence of the attention conditions as list length increased (see Figure 1). This analysis also produced main effects of age, $F(2, 64) = 24.31$, $MSE = 3.95$, $p < .001$, and attention condition, $F(1, 64) = 234.21$, $MSE = 1.25$, $p < .001$, and an interaction of age × attention condition, $F(2, 64) = 3.91$, $MSE = 1.25$, $p < .03$. The means corresponding to this interaction (see Table 2) suggest that the age effect was larger in the attended-speech condition. In pairwise Newman-Keuls tests for all of the means involved in this interaction, all pairs of means differed significantly at the $p < .05$ level, except the comparison of first graders' attended-speech memory to adults' unattended-speech memory, which happened to be at comparable levels. Thus, eliminating attention-demanding encoding strategies in adults brought them down to first grade levels, a finding matching what Cowan, Cartwright, Winterowd, and Sherk (1987) obtained by blocking rehearsal during spoken lists to be recalled.

Table 2 Interaction of Age Group and Attention Condition in Mean Number of Items Correctly Recalled

Age Group	Attended Lists	Unattended Lists
First grade	3.63 (.60)	2.41 (.71)
Fourth grade	4.50 (.73)	3.13 (.85)
Adult	5.41 (.78)	3.56 (1.05)

Note: Three first graders and two fourth graders with a span of 4 were excluded from the means reported above, but the pattern was quite similar when they were included. Each mean is across four relative list lengths. Recall of an item was recorded as correct only if the item was recalled in the correct serial position. Standard deviations are in parentheses.

In another analysis, the dependent measure was the proportion of increment in performance due to attention at the time of encoding, calculated at each list length from the number correct in the attended versus unattended conditions as the ratio: (attended − unattended) / unattended. No age effects were obtained using this ratio measure. Considering all of the results, the largest effects of age clearly occurred in both attentional conditions and could not result from encoding strategies.

Absolute list length analyses. Relative list lengths were used in this study to attain appropriate levels of task difficulty at all ages. A limitation of relative list length analyses, however, is that the list length theoretically can constrain performance. List length did not actually appear to be the limiting factor in performance. For example, when one compares adults at length span − 3 (*mean* list length = 4.38) to first graders at span (*mean* list length = 5.38), one finds a much larger number correct in the adults despite the smaller list length (Figure 1). Another indication that list length did not limit unattended-speech memory is that participants did no better with span-length lists than with lists of length span − 3. Still, to address remaining concerns, we carried out absolute list length analyses.

Each of these analyses included all participants who received lists of a particular length, except that an age group was omitted from the analysis of a particular list length if there were fewer than nine participants in that group. The eligible *N*s, *mean* correct, and ANOVA results of these analyses, carried out separately for each list length and each attention condition, are reported in Table 3. All of the list lengths that could be tested resulted in age effects for both attention conditions, except for list length 3, the shortest length that could be tested. The significant effects in the unattended-speech condition indicate that the span of apprehension increases across age groups. The age differences shown in the table actually are underestimates because the excluded participants were those with extremely high spans among adults and extremely low spans among first graders (and both extremes among fourth-grade children). The absence of an effect of age group at list length 3 could be attributed to ceiling effects.

Pairwise Newman-Keuls tests explored the cause of the age effects at list lengths 4 through 6. They were carried out for attended- and unattended-speech conditions separately. In all six of these tests, the difference between first- and fourth-grade children reached significance at $p < .03$ or better, and the difference between first-grade children and adults reached signifi-

Table 3 Age Group Effects on Memory Performance for Specific List Lengths

	N			*Mean* Correct[a]			Age Effect			
List Length	First Graders	Fourth Graders	Adult	First Graders	Fourth Graders	Adult	*F*	*df*	*MSE*	*P* <
Attended lists										
3	22	12	—	2.98	2.99	—	<1	1, 32	.00	*ns*
4	23	19	15	3.83	4.00	3.99	9.57	2, 54	.01	.001
5	21	21	22	4.30	4.85	4.82	11.51	2, 61	.04	.001
6	9	18	24	4.46	5.16	5.60	9.50	2, 48	.08	.001
7	—	12	22	—	5.40	6.17	5.79	1, 32	.11	.03
Unattended lists										
3	22	12	—	2.48	2.75	—	2.28	1, 32	.08	*ns*
4	23	19	15	2.65	3.38	2.93	4.01	2, 54	.17	.03
5	21	21	22	2.39	3.67	3.72	10.08	2, 61	.24	.001
6	9	18	24	2.22	3.28	3.57	4.18	2, 48	.24	.03
7	—	12	22	—	2.79	3.84	4.48	1, 32	.27	.05

Note: Statistical comparisons were made only for list lengths for which nine or more participants per age group produced data.

[a] Possible number correct equals the list length.

cance at $p < .02$ or better except for the unattended-speech condition at list length 4, which was not significant. Fourth-grade children, however, did not differ significantly from adults in any of these six analyses; the difference was marginal at list length 6, $p < .1$. Note from Table 3 that fourth-grade children did differ significantly from adults at list length 7, an analysis that could not include first graders.

The absence of a more consistent difference between fourth graders and adults at the shorter list lengths is especially interesting in the unattended speech condition, because it cannot be attributed to ceiling or floor effects (see Table 3). It suggests that fourth graders are about as efficient as adults in recalling items in lists up through list length 5, but that the adults can remain efficient for longer list lengths at which fourth graders falter. It is not clear if an analogous statement could be made for first graders at very low list lengths of 1 to 3 items, inasmuch as there were ceiling effects at list length 3.

In the relative list length analyses, we reported an age group × condition interaction in which the age group effect was larger in the attended-speech condition than in the unattended-speech condition. No comparable interaction was obtained in any of the absolute list length analyses. One explanation of this difference between relative and absolute list length analyses is that the range of participants was restricted in the absolute list length analyses because these can include only participants who received lists of the same length. In the shorter list length analyses, adults and fourth graders who could make the best use of attention to increase memory performance were excluded because they did not receive such low list lengths. Similarly, in the higher list length analyses, first graders who were least able to make use of attention were excluded, because they did not receive such high list lengths. Once more, the data suggest that the most important aspect of memory span development in the age range tested is unrelated to the use of attention for mnemonic encoding of the list during its presentation; the developmental trend is almost as large for unattended speech as for attended speech.

Serial position functions. Serial position functions were similar in form (though different in level) for all age groups and are shown in Figure 2 collapsed across all 72 participants, for the attended-speech (top panel) and unattended-speech (bottom panel) conditions. These functions are based on all participants who received trials at a particular list length, but list length 9 was omitted because there were too few such trials. It can be seen that performance was curvilinear across serial positions in both attention conditions, though with lower performance levels in the early list positions for the unattended-speech condition. The differential effect of a particular manipulation on the primacy (beginning) and recency (ending) portions of serial position functions has been found in other short-term memory experiments (e.g., Glanzer & Cunitz, 1966) and presumably occurs because they are mediated by different processes. The recency portion may be relatively insensitive to the attention manipulation because it makes little or no use of long-term memory mechanisms that require attention, inasmuch as the most recent items remain quite vivid in sensory mem-

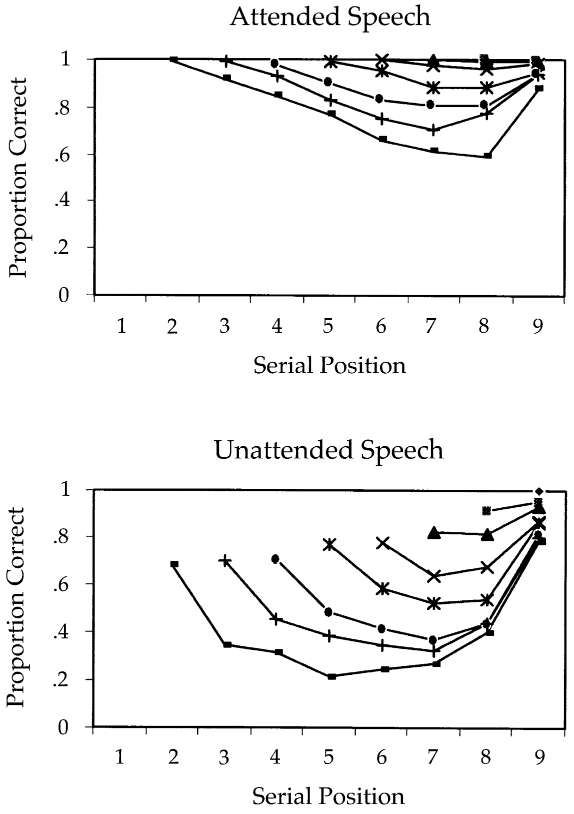

Figure 2 Mean proportion of items correct in the attended-speech (top panel) and unattended speech (bottom panel) conditions for each serial position at each list length (graph parameter). All available data were included and combined across age groups.

ory at the time of recall (see Cowan, 1995). The residual primacy effect that occurs even in the unattended-speech condition can be explained on the grounds that the beginning items of the list are demarcated by the prior inter-list silent period and, therefore, are more distinct from other items in memory than are the items in the middle of the list (e.g., Nairne et al., 1997).

The main relevance of the serial position functions is that the curvilinear function in the unattended-speech condition provides converging evidence (along with the constancy of performance across list lengths) to rule out a sensory memory decay account of the results. The presence of a primacy effect in the unattended speech condition means that the performance limit cannot be attributed to the items from the beginning of the list no longer being in sensory memory at the time of recall. Instead, a participant's attentional capacity is filled at recall with items from the most distinct portions of the sensory memory trace.

Item and order information. In the analyses reported above, each digit was considered correct only if it was recalled in the correct serial position. It is worthwhile to determine how many errors consisted of digits belonging elsewhere in the list (order errors) versus digits that were not in the stimulus list (item errors). For example, Gillam, Cowan, and Day (1995) found that children with language impairment were below children without impairment on order information in auditory short-term memory, but not on item information. To examine item information in the present data, we rescored items so that credit was given for all items from the list reported in the response, regardless of serial position. It was impossible to compare these data across list lengths, because the ease of guessing item information increases substantially across list lengths. Attended speech trials scored for item information yielded ceiling effects. Unattended speech trials yielded sufficient data at list lengths 4, 5, and 6. At each list length, the effect of age was significant: list length 4, $F(2, 54) = 4.69$, $MSE = .24$, $p < .02$; list length 5, $F(2, 61) = 19.97$, $MSE = .19$, $p < .001$; list length 6, $F(2, 48) = 5.55$, $MSE = .20$, $p < .007$. The means for the three age groups were: list length 4, 3.32, 3.78, and 3.55; list length 5, 3.99, 4.67, & 4.76; and list length 6, 5.00, 5.37, and 5.58 for first graders, fourth graders, and adults, respectively. Newman-Keuls tests showed that, at each list length, the first graders recalled fewer digits than the fourth graders, $ps < .05$, whereas in no case were the fourth graders and adults significantly different. These results indicate that the age difference in capacity between first and fourth grade includes a difference in item information, whereas the difference between fourth grade and adulthood may be restricted to order information and is generally smaller, as the previous analyses also showed.

Recall of individual digits 1–9. It could be argued that the older children recalled more digits because they were more familiar with the digits, which thus took up less capacity than in younger children (see Case et al., 1982; Dempster, 1978; Kail, 1990). To be conservative, therefore, the present result should be stated as a developmental difference in capacity to retain *digit stimuli*, with the need for future work to determine the generality across materials and theoretical reason for this developmental difference. There is one indication, however, that age differences in digit familiarity were not critical in the present procedure. Dehaene and Mehler (1992) found that the frequency of occurrence of digits in the language diminishes quickly as the numbers increase from 1 to 9. Accordingly, it could be expected that an age difference in familiarity would have a more severe effect for the larger digits. To explore this prediction, we tallied the frequency of correct recall of each of the digits 1 to 9 in the unattended-speech condition. The results indicated no tendency for small numbers to be recalled more often, in any age group. In the first grade group, the digits 1–3, 4–6, and 7–9 were recalled correctly 297, 295, and 307 times, respectively. The function was similarly flat for fourth graders (398, 396, and 386) and adults (546, 559, and 565), providing no support for the notion that familiarity dictated the age differences in memory for unattended speech. An earlier report that item familiarity can account for most age differences in span (Dempster, 1978) is puzzling, because age differences in that study were much smaller than in most others using similar stimuli (e.g., for words, Hulme, 1984; for digits, the present study).

Visual Task Performance

The visual task was carried out alone before and after the main session in which it served as a primary task along with speech sounds that were to be ignored. By comparing performance on the primary task during the single- and dual-task periods, it is possible to ask whether performance was impaired by the presence of sounds. If so, that could be taken as evidence that the sounds recruited attention to some extent away from the visual task. The reaction time (RT) and accuracy means for the visual task in each age group (Table 4) show that the means did differ, but that these significant differences reflected *better* primary task performance in the presence of the sounds than in their absence. This cannot be taken as evidence that the sounds recruited attention away from the visual task.

Why was there a significant difference in visual task performance between the visual task alone and dual task situations? Practice resulted in improvement in a monotonically decreasing, curvilinear manner, with the most improvement early on. Across age groups in the unattended speech condition, the trial-by-trial RT *means* = 4.21, 3.92, 3.67, 3.03, and 2.87 s for the first five trials and for the remaining 11 trials were relatively stable (between 2.93 and 2.34 s), illustrating the curvilinear trend. As a result, the RT average across the two visual-task-alone sessions was above the mean for the visual task in the presence of sounds averaged across the curvilinear trend. The difference is most notable in the youngest age group, for whom the visual practice effect was largest (see Table 4). Accordingly, an ANOVA of the visual task RTs in the unattended-speech condition with age group and auditory memory trials (1–16) as factors produced an effect of age group, $F(2, 69) = 68.01$, $MSE = 6.31$, $p < .001$, and of trials, $F(15, 1035) = 38.59$, $MSE = .51$, $p < .001$, as well as an age group × trials interaction, $F(30, 1035) = 6.36$, $MSE = .51$, $p < .001$ (after the Greenhouse-Geisser correction for effects involving trials), demonstrating the age differences in the magnitude of practice effects.

When one compares RTs for the initial visual-task-alone segment to visual RTs for the subsequent dual task segment culminating in the first unattended-speech memory trial, there is little difference (for first graders, 6.23 versus 6.22 s; for fourth graders, 3.99 versus 4.05 s; and for adults, 2.51 versus 2.39 s). Similarly, when one compares visual RTs for the segment culminating in the final unattended-speech memory trial to RTs for the subsequent visual-task-alone segment, again there is little difference (for first graders, 3.57 versus 3.87 s; for fourth graders, 2.47 versus 2.51 s; and for adults, 1.75 versus 1.74 s). A similar pattern was observed by Saults and Cowan (1996).

Correspondence between visual and auditory task performance. There are at least two ways in which the visual task performance theoretically could indicate that the age effects in auditory memory for supposedly unattended speech actually depended on the allocation of attention to the unattended speech. There is, however, no evidence that this occurred. First, some participants (presumably the younger ones) could have attended to the speech at the expense of performance on the visual task. Arguing against that possibility, there was no hint of a tradeoff between visual task performance and acoustic memory performance. Instead, there was a positive relation between the two across all 72 participants (between visual task

Table 4 Mean Performance of Each Age Group on the Primary (Visual) Task

	Reaction Time (s)			Proportion Correct		
Age Group	No Speech	Unattended Speech	Difference	No Speech	Unattended Speech	Difference
First grade	5.05 (1.54)	4.08 (.77)	.97**	.82 (.10)	.92 (.10)	−.10**
Fourth grade	3.29 (.85)	2.84 (.64)	.45**	.90 (.07)	.96 (.03)	−.06**
Adult	2.12 (.53)	1.97 (.41)	.15*	.95 (.04)	.98 (.01)	−.03**

Note: Standard deviations are in parentheses.
* $p < .05$, dependent *t* test; ** $p < .005$, dependent *t* test.

accuracy and unattended speech memory, $r(70) = .35$; between visual task RT and unattended speech memory, $r(70) = -.50$, negative because smaller RTs reflected better performance). Both of these correlations were significant, $p < .01$, and indicate that the participants who achieved more accurate and faster visual task performance were the same ones who achieved better auditory memory performance. Within an age group, the correlations were not significant, but they were not in the direction expected according to a tradeoff.

Second, the level of visual task performance could be interpreted as an index of task difficulty or functional load. It is theoretically possible that participants had to devote more attention to the visual task early on (given the large practice effects that were obtained), which would leave less attention to devote to the to-be-ignored auditory stimuli early on. Given that the youngest participants showed the largest practice effects, they should show their largest deficit in auditory memory (compared to older participants) early on in the unattended speech session. This was not the case. Overall, there was no systematic effect of trials on memory for unattended speech, with an average of over 3.0 digits recalled on trials 3, 4, 5, 7, 9, 10, and 16 out of 16. Moreover, in an ANOVA of memory performance in the unattended speech condition with age group and trials (1–16) as factors, the interaction of these factors did not approach significance, $F(30, 1035) = 1.18$, $MSE = 1.56$. Thus, there is no evidence that auditory memory varied as a function of the difficulty of the primary visual task, either across individuals or across trials.

DISCUSSION

In this study, a strong manipulation of attention was used to examine the role of attention in verbal short-term memory. In a seminal study within adult cognitive psychology, Sperling (1960) presented multicharacter arrays and found that recall was limited to about four characters, no matter how many characters made up the array. Presumably, this fixed limit occurred because it was not possible for the participant to encode all of the items in a categorical form, or in other terms to "upload" them from visual sensory memory to a limited-capacity store, before they faded from that store. The process of encoding (or uploading) could have started even while the items were still visible, but the essential point is that it could not proceed beyond a fixed limit. One could imagine that if the array had been presented for too long a time (e.g., 3 s), the fixed limit could be exceeded; but we would know if that happened because the number of items recalled would grow as a function of the array size, unlike what actually happened.

This same logic was adapted here for an understanding of capacity-limited storage and attention-driven processes for spoken lists of digits. This new procedure was devised to have a whole report task more suitable for children, but it also is of interest in its own right, in confirming the logic by which the capacity limit can be measured. Although only one item was presented at a time, a fixed limit was observed across list lengths provided that attention was drawn away from the spoken digits during their presentation. The attentional diversion in the unattended-speech condition may not have been complete; some items may have been encoded into a categorical form during their presentation despite the primary visual task. For example, the participant might have encoded some collection of English phonemes or syllables, and even some specific digits, despite the distraction. The observation of a fixed limit across list lengths in the unattended speech condition, however, suggests that the effects of any such recoding were not very important.

This fixed limit can be viewed as the capacity of the participant's focus of attention when reviewing the sensory memory record of the list (Cowan, 1995, in press). The finding that the recalled items include those early in the list as well as the most recent in the list (see Figure 2) indicates that the limit is not in the contents of the sensory memory record itself, but in the attention-related faculty reviewing sensory memory's contents.

Memory in the attended-speech condition may result from the same processes as unattended-speech recall, plus an additional contribution of more abstract memory codes (e.g., lexical and phonological codes) activated and/or saved in memory as the result of attention-demanding encoding during presentation of the list. These additional codes may make it easier for a partly degraded sensory trace to be used, as we will explain below. We address first the development of storage capacity, and then two additional topics relevant to the interpretation of the data: the contribution of attention and the role of recall time in memory performance.

The Development of Storage Capacity

The capacity limit was observed to increase as a function of age in childhood, no matter whether age groups were compared across list lengths defined relative to each individual's span (see Figure 1) or for particular fixed list lengths (see Table 3). This kind of result might be taken as a confirmation of previous theories suggesting that there is a short-term memory capacity that increases with development in childhood.

It could still be argued that capacity remains fixed but that the capacity required by each digit decreases with development (e.g., Dempster, 1978; Kail, 1990), although our finding of equivalent recall levels for each of the digits 1 to 9 seems inconsistent with that interpretation. In any case, the age difference in memory for unattended speech was almost as large as the age difference in memory for attended speech, demonstrating that age differences in short-term memory cannot be explained primarily by attention-demanding encoding processes taking place while the stimuli are presented.

Another theoretically-possible account of age differences in memory for unattended speech is that older participants transfer information from sensory memory to a more categorical form more quickly than younger ones, thus transferring more information before sensory memory fades. That account does not explain, however, why the age differences were as large (in fact, slightly larger) in the attended speech condition even though, in that condition, participants could transfer information from sensory memory during the list presentation, which should make this transfer rate less of a critical factor.

It is also theoretically possible that the developmental increase could have occurred because older participants did not need to devote as much attention to the primary, visual task. Several factors discussed above, however, argue against that interpretation.

1. The number of items recalled in the unattended-speech condition was roughly constant across list lengths within each age group. If some attention were allocated to the auditory stimuli during their presentation, the number recalled would be expected to increase across list lengths as in the attended-speech condition.
2. In each age group, performance in the visual task was no easier when it was performed alone than when it was performed in the presence of auditory stimuli. If attention were devoted to the to-be-ignored auditory stimuli, it would be expected to harm performance on the primary, visual task.
3. There was no tradeoff between visual and auditory task performance; individuals who did better on the visual task tended to do better on auditory memory, also.
4. There was no evidence that the level of difficulty of the visual task mattered for auditory memory performance. Visual task performance improved markedly, especially for the younger participants, during the first few trials in the unattended-speech situation, but auditory memory remained roughly constant across trials in that situation.

Still, the exact nature of the capacity limit remains uncertain. According to one hypothesis (Cowan, 1995, 1999), the limit is in the number of unconnected items or chunks that can be held in the focus of attention at one time. In the unattended-speech test condition, the limit would apply as follows. During the presentation of the list, some features of memory for each spoken item (primarily sensory features) would be automatically activated but would remain, for the most part, outside of the focus of attention. This partial activation would not be limited in quantity, although the duration of automatic activation would persist only for a limited number of seconds following the stimulus. Upon receiving the recall cue, the participant would attempt to transfer items from automatically activated memory (e.g., sensory memory) to the focus of attention. That attempt would be only partly successful because of the need to hold all of the transferred items in the same limited-capacity store concurrently after they are transferred to it. The process would be similar in the attended-speech condition except that attention during encoding would result in abstract codes and chunks of information, forming an episodic record that can be called upon during recall, to a large extent exceeding the fixed capacity limit observed for unattended speech.

There are several precedents to this finding of a development in capacity, in the visual memory literature. Haith, Morrison, Sheingold, and Mindes (1970) used a quickly flashed spatial array of one, two, three, or four shapes, and required that participants point to shapes that were present in the array. They found that 5-year-old children's performance leveled off (at about 1.5 items correct). In contrast, adults reported 3 items almost perfectly and appeared to be about 70% correct in the recall of 4-item arrays. This test was not as sensitive as the present test, because list lengths were not adjusted to take into account the participant's memory span. Sheingold (1973) presented a circular array of seven shapes followed by a teardrop-shaped indicator as a partial-report cue pointing to one item. When the partial-report cue was far enough removed in time from the array, it should provide an estimate of the asymptotically low level of performance that matches the whole report limit, according to the logic of Sperling (1960). The results suggest age differences numerically quite consistent with ours.

Another kind of evidence in favor of a capacity limit was obtained by Halford et al. (1988). They reasoned that if an item is already in some sort of short-term store (or, in their terminology, "activated"), it should not be necessary to retrieve that item. They hypothesized that proactive interference (PI), the difficulty of retrieving an item similar to a previously retrieved item, occurs during retrieval and should not apply for items that are already in the short-term store, given that they don't need to be retrieved. To examine the number that could be in the short-term store at once, they used variants of Sternberg's (1966) memory search task, in which the participant receives a list of items and then a probe item and must indicate as quickly as possible whether the probe appeared in the list. In the version of the task that they used, however, lists came in sets of three, all of which were similar in semantic category or rhyme category. Thus, the first trial in each set of three was a low-PI trial, whereas the last trial in the set was a high-PI trial. PI was obtained in adults with lists of six or more items, but not with lists of four items. Presumably, the items within a list of four did not have to be retrieved because they all could be active or present within a short-term store at the same time. In 8- to 9-year-old children, though, PI was observed with four items, but not two items in a list. This provides further evidence for the growth of a short-term storage capacity limit with age during childhood.

The Contribution of Attention during Encoding to Short-Term Memory

For lists that were attended during their presentation, the number recalled rose sharply as a function of the list length, exceeding the fixed capacity limit. Theoretically, this attentive advantage in short-term memory might be explained in several ways. First, attention may allow covert verbal rehearsal of the list items to take place. Indeed, previous work has established that attention is needed for rehearsal processes to be initiated (Guttentag, 1984). Arguing against an account based purely on rehearsal, however, the relative list length in attended-speech trials did not interact with age group (see Figure 1). If the observed rise above a fixed capacity at longer list lengths reflected primarily rehearsal, it should not be as pronounced in younger children, given that they are unlikely to engage in much rehearsal (Bjorklund & Douglas, 1997; Cowan & Kail, 1996; Flavell, Beach, & Chinsky, 1966). Another possibility is that attention is needed for the recoding of speech into categorical labels (in this case, digits). In a previous study of unattended spoken syllables in adults, Cowan, Lichty, and Grove (1990, Experiment 4) found that attention was very important for the categorical coding of consonants (though less so for vowels). In that experiment, participants read a novel in a whispered voice while ignoring spoken syllables presented over headphones. The absence of any whispered reading either during the 1-s interval before the onset of a spoken syllable or during the 1-s interval after that onset, was considered evidence of a shift of attention away from the reading, and possibly toward the spoken syllable. Such gaps in whispered reading occurred on 17% of the memory trials. Within the auditory memory test results for trials with a 1-s retention interval, memory for the consonants was 70% correct on trials with no 1-s gaps in whispered reading; but it increased to 93% correct on trials with 1-s gaps in whispered reading. This suggests that even subtle differences in attention play an important role in the encoding of consonants.

The fact that categorical labels are used in immediate memory tasks is demonstrated also by the finding that the level of recall is higher for sets of English words than for sets of nonsense words (nonwords), and that this advantage for words is found even when it takes comparable amounts of time to pronounce the words and the nonwords (Hulme, Maughan, & Brown, 1991). One reason that a categorical label is important is that participants may have to recollect items on the basis of partly degraded sensory or phonological information. The process of identifying an item and thereby restoring its full phonological representation from memory has been termed *redintegration* (Hulme et al., 1997).

In the present study, it stands to reason that identification of an item is enhanced if the participant attends to the item and therefore is able to form a categorical label for it in short-term memory at the time of the item's presentation. This categorical information in memory could be used to assist in the recollection of the list items. It could be used alone if it were vivid enough, or if it were weaker it could be used in combination with a degraded sensory or phonological memory trace, in a redintegration process. Performance would depend on this categorical information more heavily when the sensory information is degraded.

The effect of attention was found to be much larger at the earlier serial positions. This makes sense because the sensory and phonological representations would be more degraded for these early positions by the time of the memory test. Recall of the items toward the end of the list would benefit more from more vivid, automatically held auditory sensory and phonological memory traces (for reviews see Cowan, 1984, 1995; Penney, 1989). The categorical label could be derived from these lower-level forms of memory more often for the recent portions of the list, whereas the traces at earlier serial positions would be more degraded and therefore more in need of redintegration using categorical representations.

A remaining question about these data is why, at all ages, a primacy effect remained in the data in the unattended-speech condition. In contrast to an interpretation based on early models of human information processing (e.g., Atkinson & Shiffrin, 1968), rehearsal is by no means the only reason why primacy effects are obtained. They are obtained in nonhuman animals (Wright, 1994), in human infants (Cornell & Bergstrom, 1983), and in human adults for lists of nonrehearsable visual items (Neath, 1993), and may be related to the increase in temporal distinctiveness of items at both ends of a list in comparison to medial items (see Nairne et al., 1997).

The Role of Recall Time in Memory Performance

A fundamental issue in the field of short-term memory is the extent to which performance limits should be attributed to limitations in the capacity (Miller, 1956; Broadbent, 1975) versus the persistence (Baddeley, 1986) of the short-term memory representation. In the present study, a possibility that must be considered is that younger participants took longer to respond (both in the span pretest with a spoken response and in the computerized tests with a keypad response), which would allow forgetting during the response for a longer period in younger participants. Several other findings contradict this interpretation, however. First, Cowan and colleagues (1994, 1998) have examined the timing of short-term serial recall in children from 4 through 11 years of age using spoken responses and the results, considered in detail, suggest that response timing actually is an *effect* rather than a *cause* of developmental differences in performance. Although older children recalled lists of a particular fixed list length at a faster rate than did younger individuals (with the difference localized primarily to interword pauses), the rate-of-recall differences disappeared when participants were compared at lists of their own span lengths, suggesting that the recall rates served as a measure of the difficulty of the memory load for the participant, not a primary cause of the performance differences. Second, although the present research did not include response times for keypad responses, research by Cowan, Nugent, Elliott, Saults, and Ponomarev (in preparation) did, in a study to examine the loss of memory for unattended speech across test delays. They found that there were age differences in keypad RTs, but that (1) these age differences were much larger for attended lists, suggesting that they resulted largely from differences in the quality of encoding, and (2) age differences in auditory memory remained large when keypad RT was entered into the analysis as a covariate. Recall timing thus does not appear to be the underlying cause of observed capacity differences.

Conclusion

This study, which uses a new method to examine the contribution of attention to verbal short-term memory, suggests that a fixed capacity limits how much information can be drawn from an automatically encoded sensory memory into a categorical form from which information can be deliberately recalled. It further suggests a developmental increase in the effective capacity, at least for digit stimuli. Questions remain about the nature of growth in capacity and the nature of attention-related mechanisms that also may contribute to age differences in span. The striking result, though, is that age differences were nearly as large for unattended as for attended lists, despite a large mnemonic benefit of attention at all ages.

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